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**Comparing Economics of Traditional Carbonation Method and a Novel Carbonation Invention for
Craft Beer**

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Spring 2020

Department of Biological and Agricultural Engineering

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Abstract

The traditional method for the carbonation of beer includes bubbling CO₂ through a pressurized brite tank until the desired level of carbonation concentration is reached. The gas either dissolves in the liquid volume or passes through the beer into the gas headspace above the bulk volume of beer. The gas that passes through the liquid can strip the beer of flavors, and this undissolved gas is vented to the atmosphere. To reduce the gas lost to the atmosphere, the CO₂ is dissolved into the beer slowly over a long period of time, which increases gas-use efficiency but sacrifices time. The CO₂ lost to the atmosphere can also lead to increased costs and a higher carbon footprint for breweries. A carbonation invention prototype was created to address these issues; the invention aims to shorten carbonation time, reduce CO₂ waste, and lessen flavor stripping associated with the traditional method. The objective of this project is to analyze the economic differences between the traditional carbonation method and the method of the invention. The additional revenue requirements to make the method of the invention economically advantageous over the traditional method will also be determined. To compare the two methods, both methods will be scaled to a commercial size production of carbonating a 40-barrel brite tank in two hours. The rate of CO₂ delivered vs the rate of CO₂ absorbed for the two methods will be calculated based on the development of a model adapted from *Simple Model for CO₂ Absorption in a Bubbling Water Column* (Martínez and Casas, 2012). The prototype of the invention will also be scaled-up to a commercial size so that an accurate economic comparison between the two methods can be conducted.

Introduction

An invention has been created by Osborn (2018) to improve the carbonation method for craft brewing operations. The traditional method for carbonating beer involves using a diffuser stone (Figure 3) to bubble CO₂ through the beverage in a pressurized tank at a set temperature until the desired level of carbonation is reached. CO₂ gas dissolves into the beer as it is bubbled through the tank. The undissolved gas enters a headspace at the top of the tank where it is collected and vented. Through testing conducted at a local brewery during typical operations, it was estimated that only about half of the CO₂ gas that is bubbled through the liquid is dissolved, and the rest is vented to the atmosphere resulting in excess CO₂ usage. To minimize this CO₂ bleed-off, the gas can be fed into the beer very slowly, allowing time for it to dissolve, but carbonation time is extended such that it becomes a process bottleneck. Traditional carbonation can also be labor-intensive and expensive (Osborn, 2020). Additionally, bubbles passing through the beer can carry with them flavor volatiles, thereby venting them to the atmosphere. This can affect the flavor of the final product. The excess CO₂ lost to venting leads to increased costs, an increased carbon footprint, and potentially increased health hazards associated with high atmospheric CO₂ concentrations inside the brewery (Osborn, 2018). Dissolved CO₂ concentration from the carbonation is a key factor in the final quality of beer, as it impacts the mouthfeel and the flavor profile of the beverage (Langstaff and Lewis, 1993).

Method of the Invention

The invention aims to reduce CO₂ waste and thereby costs, automate carbonation control, and lessen flavor stripping associated with traditional carbonation methods. The system of the invention (Figure 1) pumps a portion of the beer from a carbonation tank (brite tank) into a pipe

where CO₂ gas is injected into the beer stream. The mixed gas/liquid (CO₂/beer) stream then enters the top of a saturation tank and is forced downward. The CO₂ bubbles dissolve into the beer in the top 20% of the saturation tank. Once the beer passes further downward, the CO₂ gas is completely dissolved into the beer for the bottom 80% of the saturation tank. The pressure in the saturation tank is typically 0.5 MPa, resulting in the formation of beer supersaturated with CO₂ in the saturation tank compared to the beer in the brite tank. The supersaturated beer is then passed back into the bulk volume of the beer in the brite tank where it completely mixes with the bulk beer such that CO₂ gas does not exit the solution as bubbles since the entire mixed bulk beer is not supersaturated. Once sufficient CO₂ gas is dissolved into beer in the brite tank such that saturation is exceeded, the CO₂ gas will escape the bulk liquid and increase the pressure in the brite tank. This increase in pressure allows the bulk beer in the brite tank to hold more dissolved CO₂, leading to an increase in dissolved CO₂ levels. According to Henry's Law, the amount of gas dissolved in a liquid is a function of gas partial pressure and liquid temperature (Incropera et al., 2007). By knowing the pressure and temperature of the beer in the brite tank, Henry's Law can be used to calculate the dissolved CO₂ concentration. Once the pressure reaches a predetermined value, and the beverage has been carbonated to an acceptable level as measured by volume CO₂ per volume beverage, the system is shut off (Osborn, 2018).

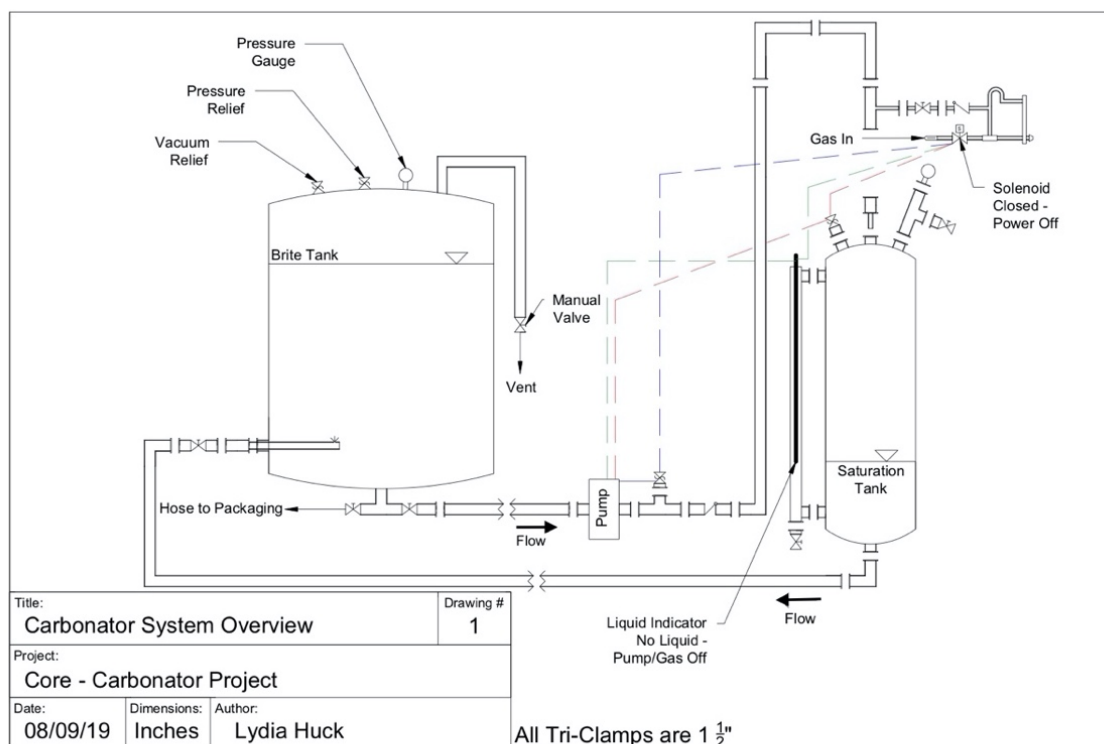


Figure 1: Carbonator System Overview, Drawing Part of Design Done by Osborn, Huck, Simonson

The goal of this research is to compare the costs of traditional bubble carbonation to the new invention. A scaled-up version of the carbonation invention prototype will be designed to determine an estimate for the capital cost of the invention. Costs between the two systems will be compared for a system to carbonate a 40-barrel brite tank in two hours. Sizing up the method of the invention to this scale allows for a reasonable comparison between the two methods to be made for a typical throughput in a craft brewery. The two-hour carbonation time was the design criteria expressed by a local craft brewery (Osborn, personal communication) for sizing of the invention. The current bubble system cannot carbonate this fast without losing efficiency, but the 2-hour time was used to make economic comparisons at the operating conditions at which the invention will be used. After designing a scaled-up system of the invention, the economic differences regarding CO₂ usage, electricity demand, and capital costs between the two methods will be evaluated. The objective of comparing the two methods is to estimate the cost differences

using modeling, labor savings using time projections from modeling, and potential improvements in revenue due to better flavor and quality. Due to the COVID-19 shutdown at the University of Arkansas during the Spring 2020 semester, flavor evaluations could not be completed. However, modeling to understand economic savings and labor reduction associated with the method of the invention was still conducted, and a plan outlining a procedure for future flavor testing was developed. Economic comparisons can identify a target for the increase in revenue that would be required for the invention to be feasible.

Review of Relevant Literature

Overview of the Craft Brewing Process

Craft brewing operations in the United States have increased rapidly over the past decade, due largely to the growth of microbreweries. The craft brewing industry has had a significant impact on the economy, contributing \$79.1 billion to the U.S. in 2018 and providing over 550,000 jobs (Brewers Association, 2018). Microbreweries are defined as having an annual production of fifteen thousand barrels or less (Brewers Association, 2018). This small-scale production presents a unique obstacle regarding carbonation and the overall brewing process, which is that craft brewers use batch systems and are not of a sufficient scale to take advantage of highly engineered systems available throughout large scale food processing operations. Craft brewing operations are generally upsizing home brewing operations rather than scaling down the highly automated and efficient processes used by large breweries. However, craft breweries desire efficiency, consistency, and maximizing profits like any other business. This presents an opportunity to engineer a system for a small-scale batch process to provide cost and labor savings while maximizing quality. The typical craft brewing steps are malting, milling, mashing,

lautering, boiling, cooling, fermentation, filtration, carbonation, and packaging. A description of each of the steps can be seen in Table 1 (BarCharts, 2017). Several of the steps have an effect on the flavors and aroma of the final product, particularly fermentation (Barth, 2013). Each of these steps will be the same for the comparison and recommended experiments, and the only process that will be changed is the carbonation method. The carbonation process is key for the final quality of the product.

Table 1: Description of Steps in the Craft Brewing Process (BarCharts, 2017)

Craft Brewing Process	Definition
Malting	<i>The grains are soaked and left to germinate before being dried to halt growth. Malting breaks down proteins and carbohydrates and releases starches that are eventually transformed into fermentable sugars.</i>
Milling	<i>Malt grains are ground into a coarse flour.</i>
Mashing	<i>Malt is mixed with hot water, and the mixture is agitated with a rake-like device. Mashing converts the starches to fermentable sugars.</i>
Lautering	<i>The sweet, sugary water, known as wort, is pumped into the brew kettle, separating the wort from the malt.</i>
Boiling	<i>The wort is boiled, and hops are added to the liquid. Hops added earlier in the boil tend to add more bitterness to the beverage, and hops added later contribute greater amounts of aroma and flavor.</i>
Cooling	<i>Once the particulate matter is removed, the liquid is cooled in a heat exchanger to a temperature appropriate for fermentation (61 °F - 72 °F for ales and 48 °F - 57 °F for lagers).</i>
Fermentation	<i>Yeast is added to covert the fermentable sugars to alcohol. Contact time between yeast and beer determines flavors developed.</i>
Filtration	<i>Solids and particulate matter in the liquid are removed.</i>
Carbonation	<i>CO₂ is dissolved in the liquid. The beer is typically cooled in a heat exchanger to 33 °F - 34 °F for this step.</i>
Packaging	<i>Beer is either canned or kegged for consumption.</i>

Henry's Law

The dissolution of a gas in liquid is governed by Henry's Law (1). Henry's law states that the amount of gas dissolved in a liquid at saturation and at a given temperature is directly proportional to the partial pressure of that gas (Incropera et al., 2007). This relationship allows

brewers to determine the amount of dissolved CO₂ in the beverage at saturation based on beer temperature and pressure.

$$X = \frac{P_v}{H} \quad (1)$$

X = mole fraction of the gas

P_v = saturation pressure of the gas

H = Henry's constant

Determining Dissolved CO₂ Concentration

Typically, brewers use a forced carbonation chart, which is a version of the data described by Henry's Law to determine what pressure is necessary to achieve the target volume of CO₂ for the beverage. This chart is based on temperature and desired volume CO₂ per volume beverage, which varies according to beer style. To determine the volume CO₂ per volume beverage, a Zahm and Nagel beer carbonation volume meter is typically used to determine temperature and pressure (Zahm and Nagel, 2019a). The meter takes a sample of beer from the brite tank and gauges the pressure of the sample through agitation to release CO₂ bubbles, which move a piston that measures the associated pressure (Zahm and Nagel, 2019a). The temperature is also determined with the Zahm and Nagel beer carbonation volume meter, shown in Figure 2.



Figure 2: Zahm and Nagel Beer Carbonation Volume Meter(Zahm and Nagel, 2019a)

CO₂ concentration can also be determined with a Gehaltemeter, which can take both dissolved CO₂ and dissolved O₂ readings. The Gehaltemeter is an automated instrument that measures the volume CO₂ per volume beverage using an equation similar to Henry's Law through an inlet stream and outlet stream (Haffmans, 2015). Osborn (2018) created equation 2 to represent the data in the Zahm and Nagel chart. The chart was used because most craft brewers have calibrated their carbonation requirements to the data on the chart.

$$P = (C \times 0.0013493 \times T^2 + C \times 0.094214 \times T + C \times 4.81904) - 14.7 \quad (2)$$

P = pressure of the beer in the tank at the desired concentration (psi)

C = desired concentration of CO₂ in the volume (volume CO₂/volume beer)

T = temperature of the beer (degrees Fahrenheit)

Forced Carbonation

The traditional method for carbonating beer relies on pumping a stream of CO₂ gas through a carbonation stone (Figure 3) placed at the bottom of the beer in a brite tank. As the gas

passes through the stone, small bubbles form and pass upward through the liquid beer. The gas bubbles either dissolve into the beer or exit the liquid into the gas headspace above the liquid. As undissolved gas is added to the headspace, the pressure in the tank increases because of the added gas volume. The pressure in the brite tank is typically controlled to the desired pressure from the forced carbonation chart by venting the gas at the rate required to maintain the pressure. This venting results in lost CO₂. Brite tanks are rated to withstand a specific pressure, so a pressure relief valve can also vent gas if the pressure is too high.



Figure 3: Carbonation Stone (Cellar Supply, 2019)

Determining Dissolved CO₂ Concentration Using Method of Invention

The invention carbonates the beer by pumping a side stream out of the brite tank through a series of processes that dissolve CO₂ into the liquid and reintroduce it to the bulk beer in the brite tank with no bubbles. Since the invention does not add bubbles to the brite tank, the flow rate of liquid into the brite tank equals the flow rate of liquid out of the brite tank, meaning there is no volume added to the system. Since there is no increase in volume in the brite tank, there is no increase in pressure except that caused by supersaturation gas in the bulk beer escaping to

increase the pressure in the brite tank. Therefore, all pressure increases correlate to the pressure caused by carbonation equilibrium in the beer. Thus, as with the Zahm and Nagel meter, pressure and temperature can be used with the chart to determine dissolved CO₂ concentration, or entered into other Henry's Law based equations such as equation 2. This means that a pressure gauge and thermometer can be used to indicate the carbonation level continuously and automatically, which reduces operator labor associating with collecting manual measurements (Osborn, 2018).

Food Safety and Brewing

It is generally assumed that there are limited pathogenic risks associated with the production of beer. However, an experiment was conducted to determine the ability of various pathogens to survive under different conditions in beer to confirm this knowledge (Menz et al., 2011). The experiment found that there is a very low risk of pathogen survival in full-strength, bottled beer. This confirms the widely accepted assumption that several conditions that exist in beer make pathogen survival and growth very unlikely (low pH, the presence of ethanol, elevated CO₂, and low oxygen). Additionally, external processes such as pasteurization, boiling, filtration, and cold storage make the presence of pathogens even more unlikely. The low probability of pathogen survival in beer means that unsatisfactory food safety in the brewing process is a low risk.

Flavor Profiles of Beer

Beers can be broadly classified into four families, determined by fermentation and conditioning: ales, lagers, mixed-fermentation beers, and hybrid beers. Ales tend towards a profile of fruitiness, lagers typically are known for their crisp and clean flavors, mixed

fermentation beers can have musty, tart, and tangy flavors, and hybrid beers can have a variety of flavor profiles (BarCharts, 2017). Differentiation of beer families requires different carbonation concentrations, among other factors.

The flavor components of beer are influenced by bitterness, sweetness, sourness, and saltiness. Much of the flavor of a beer is determined through aroma, or the so-called “nose” of the beer (Bamforth, 2016). The carbonation process is key for the final quality of beer. A lack of proper carbonation can significantly impact the perceived condition of the beer (Briggs et al., 2004). A literature review compiled by Langstaff and Lewis (1993) found that carbonation is one of the three most important elements contributing to the mouthfeel of the beer. The two other factors contributing to the mouthfeel of beer and their sub-components are shown in Figure 4.

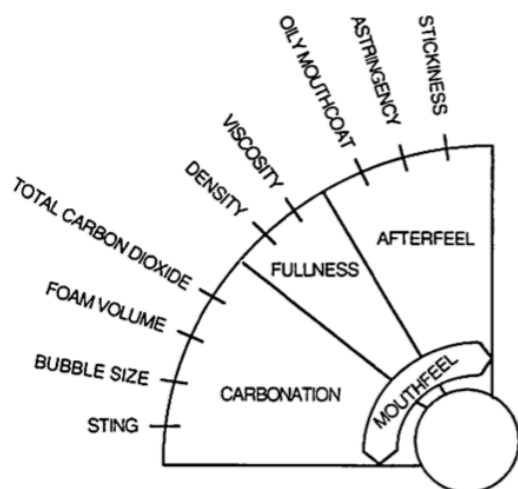


Figure 4: Components of Mouthfeel of Beer (Langstaff and Lewis, 1993)

The mouthfeel of beer is one component within the larger Beer Flavor Wheel (Figure 5) developed by Meilgaard et al. to summarize the flavor descriptors of beer (Meilgaard et al., 1979). The Beer Flavor Wheel has been accepted as the industry standard for describing the

flavorsome components of beer for the last 40 years. It has been revised and modified by several organizations over time, but the basis for the flavor descriptors has remained unchanged.

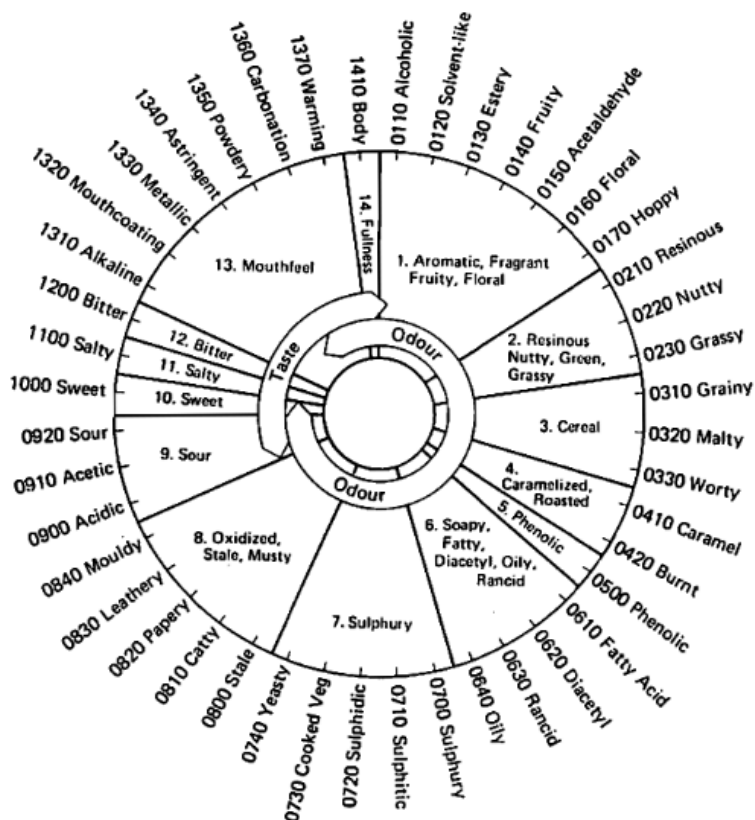


Figure 5: Beer Flavor Wheel(Meilgaard et al., 1979)

Design Process

Model for Rate of CO₂ Delivered for Traditional Carbonation Method

A quantified relationship between rate of CO₂ bubbling into beer and carbonation rate could not be found in the literature. Anecdotal data from Moravek (2018) indicates that traditional bubble force carbonation operated in an optimal manner results in a 35% waste of CO₂ gas. Osborn (2020) measured the gas flow rate exiting the brite tank during a force carbonation process when the gas flow rate was increased to reduce carbonation time from the typical 8 hours to 4 hours and found 47% of CO₂ gas was wasted. To determine this relationship

for the traditional carbonation method, a model was developed and adapted from a *Simple Model for CO₂ Absorption in a Bubbling Water Column* (Martínez and Casas, 2012). Beyond estimations collected from field testing, there was not a concrete mathematical model comparing the rates between the traditional and invention methods. It is necessary to understand the discrepancy in the rate of CO₂ delivered and CO₂ absorbed so that a cost comparison analysis between the traditional carbonation method and the invention can be made. In this model, the carbonation rate of beer in kilograms of CO₂ per kilogram of beer per second can be determined based on a multitude of parameters within the system. This rate is defined in equation 3.

$$\frac{dw_{\infty}}{dt} = \frac{27\nu_1 D_g u_g}{2gr_0^4} (w_0 - w_{\infty}) \quad (3)$$

$$\frac{dw_{\infty}}{dt} = \text{carbonation rate of beer (kg CO}_2\text{/kg beer/s)}$$

$$\nu_1 = \text{kinematic viscosity of beer (m}^2\text{/s)}$$

$$D_g = \text{gas diffusivity of CO}_2 \text{ (m}^2\text{/s)}$$

$$u_g = \text{gas injection speed (m/s)}$$

$$w_0 = \text{gas mass fraction in gas bubble, constant (kg CO}_2\text{/kg beer)}$$

$$w_{\infty} = \text{gas mass fraction in gas bubble at any point in time (kg CO}_2\text{/kg beer)}$$

$$g = \text{gravitational constant (m/s}^2\text{)}$$

$$r_0 = \text{mean gas bubble radius (m)}$$

Equation 3 in the original work does not account for the changing rate over time as the concentration of dissolved gas in liquid increases. For this work, equation 3 was used in a timestep model to determine the amount of CO₂ in kilograms added per kilogram of beer in the system over one-second intervals. After each one second time step, the concentration of dissolved gas in the beer was changed based on the rate calculated in the previous time step and

become the beer concentration (w_∞) for the next time step. This allowed carbonation rates to be estimated for different volumetric flow rates of CO₂. The kinematic viscosity of beer is given as 1.8×10^{-6} m²/s and the gas diffusivity of CO₂ is given as 1×10^{-9} m²/s (Engineering Toolbox, 2020a, 2020b). The gas injection speed is dependent on the volumetric gas flow of CO₂ into the system and the cross-sectional area of the brite tank. Therefore, the gas injection speed can be calculated by equation 4. The cross-sectional area of the 40-barrel brite tank being carbonated for comparison between the two methods is given as 2.41 m².

$$u_g = \frac{Q}{A} \quad (4)$$

u_g = gas injection speed (m/s)

Q = volumetric flow of CO₂ into system (m³/s)

A = cross-sectional area of brite tank (m²)

W_0 is based on the pressure in the bubble, which is dependent on both the gas headspace pressure and the hydrostatic pressure in the brite tank. The headspace pressure is given as 16 psi (required to carbonate the beer to a target concentration of 3.0 vol/vol) and the hydrostatic pressure is calculated by equation 5.

$$P_h = \rho gh \quad (5)$$

P_h = hydrostatic pressure (pascals)

ρ = fluid density (kg/m³)

g = gravitational constant (m/s²)

h = average tank height (m)

The fluid density is given as 1030 kg/m^3 (Anheuser-Busch, 2000), gravity is given as 9.81 m/s^2 , and the average tank height for a 40-barrel brite tank is 0.95 m . From these values, the hydrostatic pressure is calculated as 9599 Pa (1.392 psi). Therefore, using equation 2, it can be determined that for 17.4 psi and $34 \text{ degrees Fahrenheit}$, the volumetric concentration of CO_2 per volume of beer is 3.35 vol/vol . Converting to a mass ratio yields:

$$w_0 = \frac{3.35 \text{ vol } \text{CO}_2}{\text{vol beer}} \times \frac{1.977 \text{ kg } \text{CO}_2}{\text{m}^3 \text{ CO}_2} \times \frac{\text{m}^3 \text{ beer}}{1030 \text{ kg}} = 6.43 \times 10^{-3} \frac{\text{kg } \text{CO}_2}{\text{kg beer}}$$

The assumed starting concentration of CO_2 , $W_{\infty(\text{initial})}$, was 1.0 vol/vol and the desired final concentration of CO_2 , $W_{\infty(\text{final})}$, was set as 3.0 vol/vol . Each of these values was converted to kg CO_2 per kg beer :

$$w_{\infty(\text{initial})} = \frac{1.0 \text{ vol } \text{CO}_2}{\text{vol beer}} \times \frac{1.977 \text{ kg } \text{CO}_2}{\text{m}^3 \text{ CO}_2} \times \frac{\text{m}^3 \text{ beer}}{1030 \text{ kg}} = 1.92 \times 10^{-3} \frac{\text{kg } \text{CO}_2}{\text{kg beer}}$$

$$w_{\infty(\text{final})} = \frac{3.0 \text{ vol } \text{CO}_2}{\text{vol beer}} \times \frac{1.977 \text{ kg } \text{CO}_2}{\text{m}^3 \text{ CO}_2} \times \frac{\text{m}^3 \text{ beer}}{1030 \text{ kg}} = 5.76 \times 10^{-3} \frac{\text{kg } \text{CO}_2}{\text{kg beer}}$$

The mean bubble radius used in the original paper was 0.19 mm based on several assumptions. For this problem, the bubble radius had to be adjusted for the bounds of this system so that the initial calculated CO_2 uptake rate did not exceed the rate of CO_2 delivered, which is not possible. The mean bubble radius was set as $2.69 \times 10^{-4} \text{ m}$ by solving for the bubble size that resulted in the CO_2 uptake rate being equal to the delivery rate when carbonation was started. Using the adapted model, the gas flow rate was determined so that the desired final concentration of CO_2 (3.0 vol/vol) occurred after two hours of carbonation to match the carbonation time for which the invention was designed. The gas flow rate was determined by iterating different values for the volumetric flow of CO_2 gas into the system until the desired carbonation concentration goal was reached. A summary of the values used in the adjusted model is shown in Table 2.

Table 2: Parameters for equation to determine carbonation rate of beer

Parameter	Value
$\nu_1 = \text{kinematic viscosity of beer (m}^2/\text{s)}$	1.8×10^{-6}
$D_g = \text{gas diffusivity of CO}_2 \text{ (m}^2/\text{s)}$	1×10^{-9}
$u_g = \text{gas injection speed (m/s)}$	5.60×10^{-4}
$w_0 = \text{gas mass fraction in gas bubble, constant (kg CO}_2/\text{kg beer)}$	6.43×10^{-3}
$g = \text{gravitational constant (m/s}^2)$	9.81
$r_0 = \text{mean gas bubble radius (m)}$	2.69×10^{-4}

The model was carried out for 7200 one-second timesteps with the result being that the target concentration of 3.0 vol/vol occurring at 2 hours with a flow rate of 80.8 LPM of CO₂ gas at a pressure of 17.4 psig. For each timestep, starting with 1 second, $\frac{dw_\infty}{dt}$ was calculated based on the w_∞ value from the timestep before. For the first timestep, $\frac{dw_\infty}{dt}$ was calculated by:

$$\begin{aligned} \frac{dw_\infty}{dt} &= \frac{27 \times 1.8 \times 10^{-6} \times 1 \times 10^{-9} \times 5.60 \times 10^{-4}}{2 \times 9.81 \times (2.69 \times 10^{-4})^4} \times (6.43 \times 10^{-3} - 1.92 \times 10^{-3}) \\ &= 1.19377 \times 10^{-6} \frac{\text{kg CO}_2}{\text{kg beer} - \text{s}} \end{aligned}$$

This means that 1.19377×10^{-6} kg CO₂/kg beer was added in the first second. The value of w_∞ for the next time step then becomes $w_{\infty-1} + \frac{dw_\infty}{dt} \times dt$, where dt was 1 second.

The system is a 40-barrel brite tank, which is equivalent to:

$$40 \text{ barrel} \times \frac{31 \text{ gal}}{\text{barrel}} \times \frac{3.785 \text{ L}}{\text{gal}} \times \frac{1030 \text{ g}}{\text{L}} \times \frac{\text{kg}}{1000 \text{ g}} = 4835 \text{ kg beer}$$

So, after the first timestep, the rate of CO₂ added to the system is:

$$1.19377 \times 10^{-6} \frac{\text{kg CO}_2}{\text{kg beer} - \text{s}} \times 4835 \text{ kg beer} = 5.77 \times 10^{-3} \text{ kg/sec}$$

This process was carried out for 7200 timesteps, which is summarized in Table 3.

Table 3: Summary of timesteps for adapted CO₂ uptake model

Time (seconds)	$\frac{dw_{\infty}}{dt}$ (kg CO ₂ /kg beer/s)	w_{∞} (kg CO ₂ /kg beer)	kg CO ₂ /s	g CO ₂ /min	Target Concentration Met?
0		0.001919417			Below Target
1	1.19377E-06	0.001920611	0.005771531	346.2918882	Below Target
2	1.19345E-06	0.001921805	0.005770003	346.2002078	Below Target
3	1.19314E-06	0.001922998	0.005768476	346.1085517	Below Target
4	1.19282E-06	0.001924191	0.005766949	346.0169199	Below Target
5	1.19251E-06	0.001925383	0.005765422	345.9253123	Below Target
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7195	1.77686E-07	0.00575751	0.000859059	51.54351971	Below Target
7196	1.77639E-07	0.005757688	0.000858831	51.52987362	Below Target
7197	1.77591E-07	0.005757865	0.000858604	51.51623115	Below Target
7198	1.77544E-07	0.005758043	0.000858377	51.50259228	Below Target
7199	1.77497E-07	0.00575822	0.000858149	51.48895703	Below Target
7200	1.7745E-07	0.005758398	0.000857922	51.47532539	Target Reached

Note that the model predicts that the absorption rate decreases as the concentration of CO₂ in the beer increases over time, as would be expected for a gradient driven process such as diffusion of gas from a bubble into liquid. A plot of the increase of CO₂ concentration over time, as measured by vol CO₂ per vol beer for the adapted model, can be seen in Figure 6.

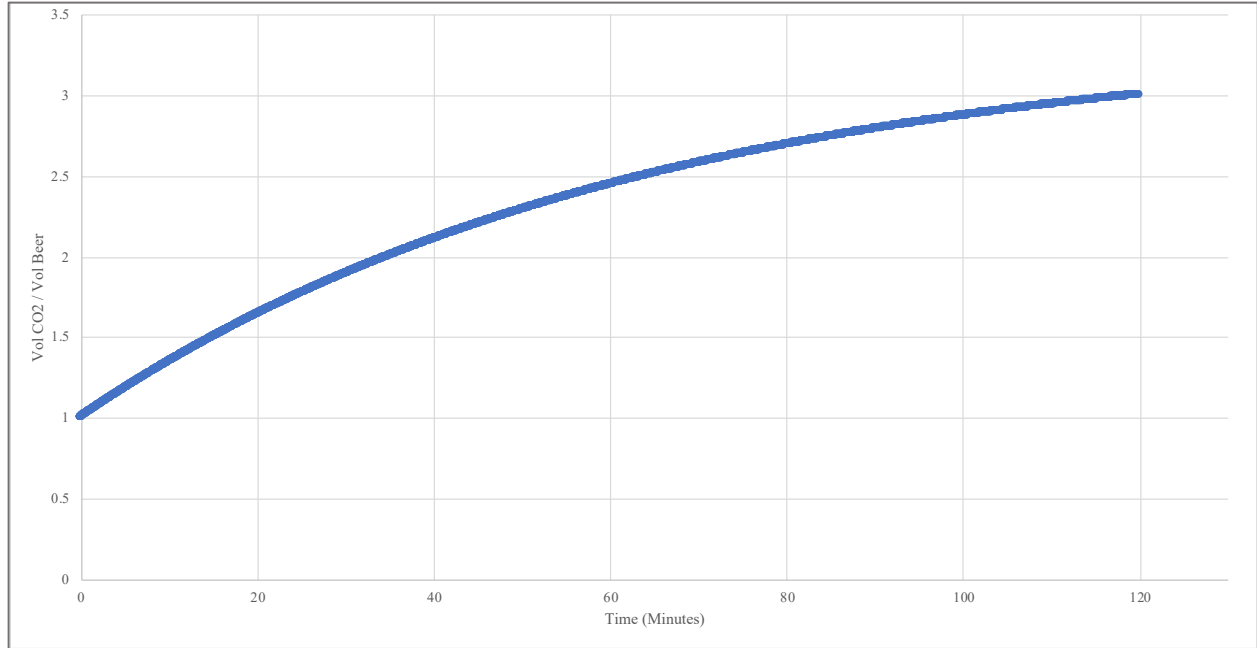


Figure 6: Change in the volume of CO₂ per volume beer over time

As stated, the necessary volumetric flow rate of CO₂ into the system to meet the goal concentration in 2 hours is 80.8 LPM of gas at the pressure of the bubble. Converted to SLMP based on the absolute pressure in the tank by the ideal gas law $P_1V_1 = P_2V_2$:

$$SLPM = \frac{80.8 \text{ LPM} \times 32.092 \text{ psi}}{14.7 \text{ psi}} = 176.3 \text{ SLPM}$$

Which can be converted to grams of CO₂ delivered per minute using the density of CO₂ at standard conditions (T=0 °C, P= standard atmosphere 0 psig):

$$176.3 \text{ SLPM} \times \frac{1.977 \text{ g}}{\text{L}} = 348.59 \frac{\text{g CO}_2}{\text{minute}}$$

The rate of CO₂ delivered can be compared to the uptake rate of CO₂ by the beer to determine the efficiency of the carbonation system. The difference in the initial w_∞ value and the target w_∞ value can be used to calculate the average rate of CO₂ taken up by the beer:

$$\left(5.76 \times \frac{kg\ CO_2}{kg\ beer} - 1.92 \times 10^{-3} \frac{kg\ CO_2}{kg\ beer}\right) \times \frac{1030\ kg\ beer}{L} \times 40\ barrel \times 31 \frac{gal}{L} \times 3.785\ L$$

$$= 18560\ kg\ CO_2\ added$$

$$\frac{18560\ kg\ CO_2}{120\ min} = \frac{154.66\ g\ CO_2\ added}{min}$$

Therefore, the efficiency of CO₂ usage is:

$$\frac{154.66\ g/min\ absorbed}{348.59\ g/min\ delivered} = 44\%$$

56% of the CO₂ used by the system is lost. This excess CO₂ usage is eliminated by the method of the invention since the rate of CO₂ added to the brite tank will be sized to be a near-constant 154.66 g/min. This added efficiency will decrease costs and potentially harmful CO₂ emissions.

Rate of CO₂ Uptake for Method of Invention

The prototype of the invention was used to carbonate beer (Prison Break Larry) at Core Brewing (Springdale, AR) and apple cider at Black Apple Crossing (Springdale, AR) during several tests performed by Osborn and Huck (Osborn, 2020). During these tests, a wide range of data was collected, part of which was used to determine the carbonation rate for the method of the invention. The data from the tests where the prototype was fully and continuously operating were used to estimate the rate of CO₂ uptake by the beer in the brite tank. These tests allowed for the carbonation rate in grams of CO₂ per minute to be estimated based on Gehaltemeter readings over time, pressure and temperature readings in the brite tank being converted to vol/vol concentration over time, and gas flow meter readings. For the beer test at Core Brewing only, Gehaltemeter readings were collected using a Model-c DGM CO₂/O₂ Gehaltemeter made by Haffmans BV (Venlo, Netherlands). Readings could not be collected continuously in real time as could the brite tank pressure and gas flow rate readings. To collect a Gehaltemeter reading, the

carbonator had to temporarily stop operation and three samples were collected with each sample collection requiring that the meter be rinsed with beer for 30 seconds, then filled for testing, then the testing procedure executed to provide a vol/vol concentration of dissolved CO₂ in the beer.

The entire procedure required that the carbonation process be paused for approximately 30 minutes. For some of the tests, the Gehaltemeter readings did not provide usable data.

Gehaltemeter readings were not collected for cider samples as a meter was not available for use.

A sample of the data used to determine the CO₂ uptake rate for each method can be seen in Figure 7.

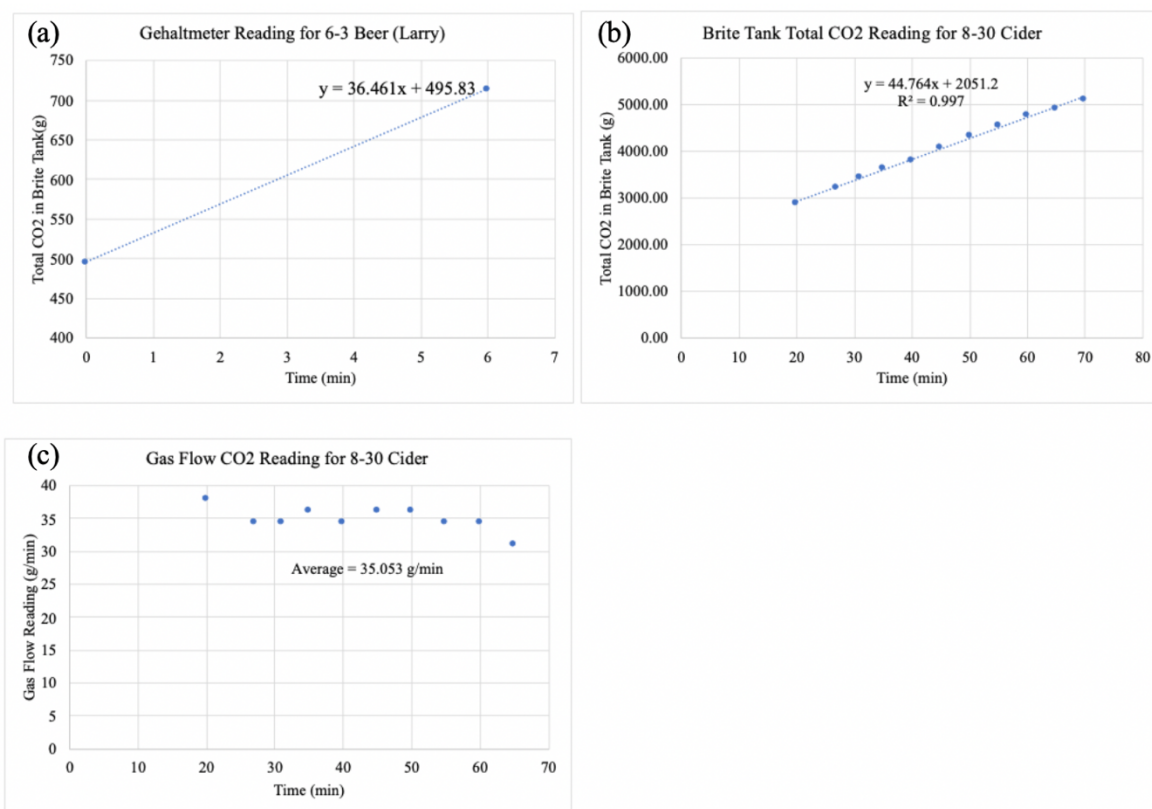


Figure 7: CO₂ uptake rate sample reading for (a) Gehaltemeter, (b) brite tank pressure, and (c) gas flow meter

For each method of determining CO₂ uptake rate, the average and standard deviation of the results were calculated. None of the data points were more than 3 standard deviations away

from the average, so all data was used in the calculation of the average uptake rate. The mean of the average uptake rate for each measurement method was used as the final CO₂ uptake rate for scaling-up the system. A summary of this data can be seen in Table 4.

Table 4: CO₂ uptake readings for the method of the invention based on Gehaltemeter, tank pressure, and gas flow meter readings

Test ID	Gehaltemeter (g CO ₂ /min)	Brite Tank Pressure (g CO ₂ /min)	Gas Flow Meter (g CO ₂ /min)	
2-25 Beer (Mix)	29.04	45.23	37.99	
2-25 Beer (Mix)	37.85	43.66	37.99	
5-24 Beer (Larry)	84.65	44.01	34.53	
5-24 Beer (Larry)		126.31	33.67	
6-3 Beer (Larry)	64.18	42.51	33.38	
6-3 Beer (Larry)	36.46	51.75	32.81	
8-21 Cider		17.61	28.37	
8-30 Cider		44.76	35.05	
9-1 Cider		47.36	36.53	
				Final Average
Average	50.44	51.47	34.48	45.46
Standard Deviation	23.30	29.68	2.98	
3 X Standard Dev.	69.90	89.03	8.94	
Lower Range	-19.46	-37.56	25.54	
Upper Range	120.33	140.49	43.42	

Size-Up Design of Method of Invention Based on Calculated CO₂ Uptake Rate

To compare the traditional method and the method of the invention the prototype of the invention needed to be scaled-up so that each method carbonated a 40-barrel brite tank in 2 hours. To carbonate the liquid volume from 1.0 vol/vol to 3.0 vol/vol in 2 hours it is necessary to calculate the required mass of CO₂ to be added to the system:

$$\Delta CO_2 = \frac{2.0 \text{ vol } CO_2}{\text{vol beer}} \times \frac{1.977 \text{ g } CO_2}{L} \times (40 \text{ barrel}) \times \frac{31 \text{ gal}}{\text{barrel}} \times \frac{3.785 L}{\text{gal}} = 18558 \text{ g } CO_2$$

The method of invention was sized up from the original prototype using the calculated CO₂ uptake rate of 45.56 grams per minute. The prototype had a measured side stream flow rate of 1.94 gallons per minute. From these values, the required flow rate of the sized-up system can be determined:

$$\frac{1.94 \text{ gal beer}}{\text{min}} \times \frac{\text{min}}{45.56 \text{ g CO}_2} \times \frac{18588 \text{ g CO}_2}{120 \text{ min}} \times \frac{3.785 \text{ L}}{\text{gal}} \times \frac{\text{m}^3}{1000 \text{ L}} \times \frac{60 \text{ min}}{\text{hr}} = 1.50 \text{ m}^3/\text{hr}$$

$$= 0.000415 \text{ m}^3/\text{s}$$

To size the piping based on these values, an initial guess velocity of 1 m/s was used. The cross-sectional area of the pipe was calculated by:

$$\frac{1.50 \text{ m}^3}{\text{hr}} \times \frac{\text{hr}}{3600 \text{ s}} \times \frac{\text{s}}{1 \text{ m}} = 0.000415 \text{ m}^2$$

The calculated area has a diameter of 0.905 inches, so 1" 16-gauge sanitary tubing with an internal diameter (ID) of 0.87 inches (0.0221m) and a cross-sectional area of 0.0278 m² was selected. The actual velocity based on this ID becomes 1.08 m/s. This velocity is sufficiently low to prevent high pressure losses from friction while providing for a reasonably sized hose.

The saturation tank of the prototype has a 4" SCH 40 PVC pipe with an ID of 4.09 inches (0.1023 m) and a cross-sectional area of 0.0082 m². Using the known flow of 1.94 gpm (1.22 × 10⁻⁴ m³/s), the velocity through the saturation tank is calculated as 0.0149 m/s. Using this velocity and the previously calculated volumetric flow of the sized-up system, 0.000415 m³/s, the cross-sectional area of the scaled-up saturation tank is calculated as 0.0279 m² with an ID of 7.42 in (0.1884 m). Based on this calculated ID, 8" SCH40 pipe with an ID of 7.943 in (0.2017m) was selected, for a final velocity of 0.0130 m/s.

The prototype saturation tank height is 3 feet and is 80% full of liquid. The retention time in the saturation tank can then be calculated:

$$3 \text{ ft} \times 80\% \times \frac{s}{0.0149m} \times \frac{0.3048m}{ft} = 49.09 \text{ seconds}$$

Based on this retention time, the required height of the sized-up system can be calculated:

$$\frac{0.0130 \text{ m}}{s} \times \frac{49.09s}{80\%} \times \frac{ft}{0.3048m} = 2.09ft$$

For the prototype, the nozzle through which the beer and injected gas pass into the saturation tank has a reduction from 3/4" SCH40 PVC piping to 1/8" SCH40 PVC piping. The cross-sectional areas of each pipe are $3.44 \times 10^{-4} \text{ m}^2$ and $3.67 \times 10^{-5} \text{ m}^2$, respectively. The velocity for each pipe is calculated by Q/A so that $V_{\text{big}} = 3.56 \times 10^{-1} \text{ m/s}$ and $V_{\text{small}} = 3.34 \text{ m/s}$. The ID of the larger pipe, D_1 , is 0.0209m and the ID of the smaller pipe, D_2 is 0.0068m. The K value can be solved for by (EnggCyclopedia, 2019):

$$K = 0.5 \left(1 - \frac{D_2^2}{D_1^2} \right) = 0.5 \left(1 - \frac{(0.0068m)^2}{(0.0209m)^2} \right) = 0.4467$$

The pressure drop across the reduction is:

$$\begin{aligned} \Delta P &= \frac{K \times v_{\text{small}}^2}{2g} \times \rho \times g = \frac{0.4467 \times \left(3.34 \frac{m}{s} \right)^2}{2 \times 9.81 \frac{m}{s^2}} \times (1030 \text{ kg beer})/m^3 \times 9.81 \frac{m}{s^2} \\ &= 2562 \text{ Pa} \end{aligned}$$

The size of nozzle into the saturation tank can be calculated based on the volumetric flow of the sized-up system, $0.000415 \text{ m}^3/\text{s}$, and the V_{small} from the prototype. Q/V yields an area with an ID of 0.496 in (0.0126 m). Based on this value, 3/8" SCH40 piping with an ID of 0.493 inches (0.0125 m) is selected so that the new velocity becomes 3.37 m/s for the sized-up system. The K

value is solved for using $D_1 = 0.0221$ m and $D_2 = 0.0126$ m so that K is 0.3394. The associated pressure drop is:

$$\Delta P = \frac{K \times v_{small}^2}{2g} \times \rho \times g = \frac{0.3394 \times \left(3.37 \frac{m}{s}\right)^2}{2 \times 9.81 \frac{m}{s^2}} \times (1030 \text{ kg beer})/m^3 \times 9.81 \frac{m}{s^2}$$

$$= 1989 \text{ Pa}$$

To calculate the friction losses from the reduction, the work is calculated from the velocity head:

$$Work = \frac{0.339 \times \left(3.37 \frac{m}{s}\right)^2}{2 \times 9.81 \frac{m}{s^2}} = 0.197m$$

Reynold's number is calculated through density, V_{small} , D_{small} , and dynamic viscosity (Engineering Toolbox, 2020c) of the fluid:

$$Re = \frac{(\rho V D)}{\mu} = \frac{\frac{1030 \text{ kg}}{m^3} \times \frac{3.37 m}{s} \times 0.0126 m}{0.0018 \text{ Pa} \cdot s} = 24172$$

The roughness coefficient, ϵ , for PVC is 0.046mm. ϵ/D is then 0.0037, and the friction factor, f , can be read as 0.0032 from a Moody diagram. Using the same nozzle length as the prototype, 1", friction losses are calculated as:

$$F = f \times \frac{L}{D} \times \frac{v^2}{2g} = 0.0032 \times \frac{0.0254 m}{0.0126 m} \times \frac{\left(3.37 \frac{m}{s}\right)^2}{2 \times 9.81 \frac{m}{s^2}} = 0.039m$$

The total work required by the system due to the reduction is then:

$$0.039m + 0.197m = 0.236m$$

This converts to a pressure of:

$$0.236 m \times 1030 \frac{kg}{m^3} \times 9.81 \frac{m}{s^2} = 2385 \text{ Pa}$$

The final system requirements are summarized in Table 5 and Figure 8 for the scaled-up model.

Figure 8 is a diagram of the original prototype with updated dimensions for the scaled-up model.

Table 5: Final scaled-up system requirements

Part of System	Scaled-Up Value
Side stream flow	1.4956 m ³ /hr
Pipe size	1" 16-gauge sanitary tubing (ID = 0.02210 m)
Saturation tank diameter	8" SCH40 (ID = 0.2017 m)
Saturation tank height	2.6 ft
Nozzle into sat. tank size	3/8" SCH40 (ID = 0.0125 m)
Pressure requirement	2385 Pa
Pump requirement	75 psi

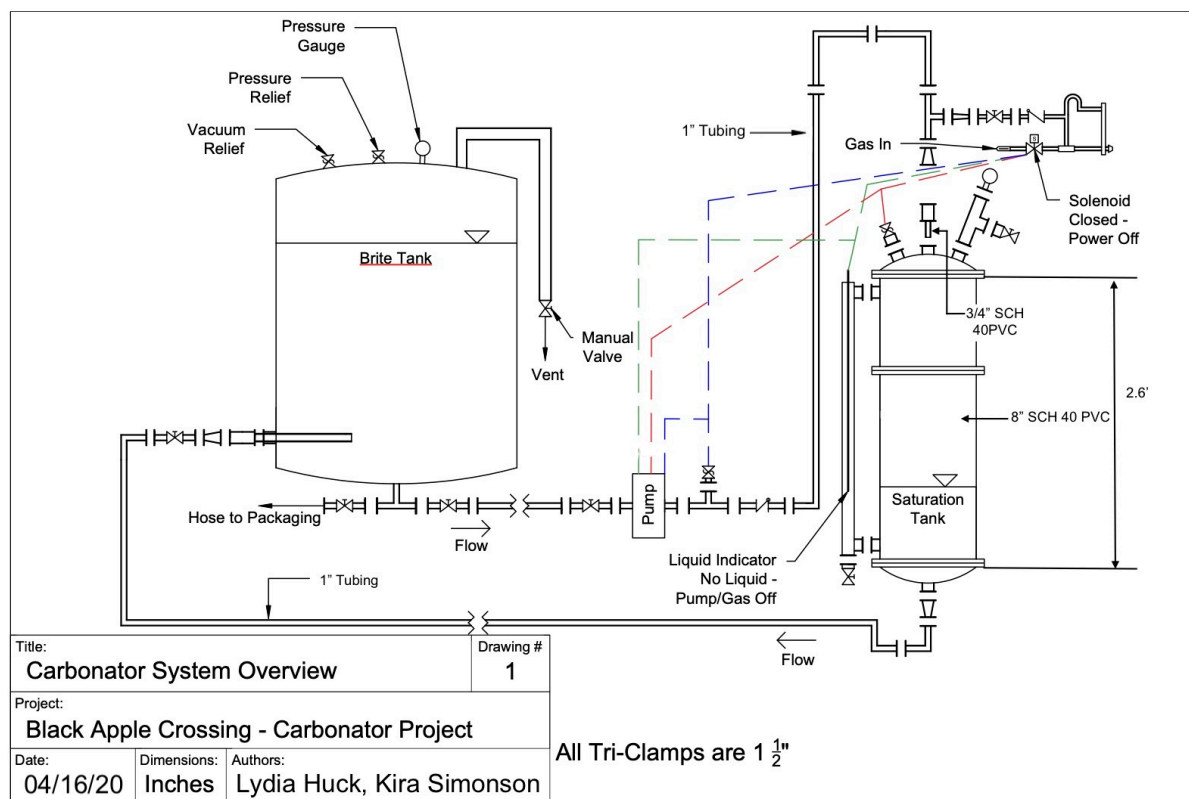


Figure 8: Overview of scaled-up system with dimensions

Comparison of Systems

Economic Comparison

All economic comparisons were made for a two-hour carbonation time for adding 2.0 vol/vol of CO₂ to beer for a 40-barrel brite tank. The total CO₂ use of the traditional bubble method is an average (since the rate is not constant) of 348.59 g/min over 120 minutes for a total CO₂ use of 41830 g. The total CO₂ use of the method of the invention is 154.66 g/min (constant) over 120 minutes for a total CO₂ use of 18560 g. The price of purchased CO₂ gas was assumed to be \$0.374/kg which includes gas purchase and equipment rental for the Northwest Arkansas area (Osborn, 2020). The annual cost of CO₂ use can be estimated based on an annual production of 450 40-barrel batches, which is the production of a mid-size regional brewery that would be slightly larger than a microbrewery (Brewers Association, 2018) (Table 6).

Table 6: Economic comparison of carbonation methods for CO₂ usage

	Total CO₂ use per batch (kg)	Cost per 40-barrel batch	Cost per barrel beer	Batches per year	Annual CO₂ cost
Traditional method	41.83	\$15.64	\$0.39	450	\$7,040.12
Method of invention	18.56	\$6.94	\$0.17	450	\$3,123.59

The electricity costs of the method of the invention can be calculated from the energy required by the pump. The pump will have a flow rate of 0.000415 m³/s and a pressure output of 75psi (517107 Pa). Friction losses were also accounted for as 2385 Pa. Multiplying these together yields a delivered power of 0.216 kW. The required pump power assuming 60% pump/motor efficiency (typical for a food grade, continuous duty pump) is then 0.360kW. Assuming an electricity cost of \$0.10/kW-hr and an operating time of 2 hours per batch, the

electricity cost per batch becomes \$0.0719. With an annual production of 450 batches, the yearly electricity cost for operating the pump is \$32.37.

The capital costs of the method of the invention are estimated by doubling the cost of components \$8500 (Huck, 2020 cost compiled for the prototype as part of MS project), so price to the customer is estimated to be double the material costs, so that the initial investment of the manufacturer can be recovered and a reasonable profit attained. The annual savings that the method of the invention provides, based on CO₂ and electricity costs are \$3884.15. The simple payback period for the client to earn back their initial capital investment is 4.38 years (Table 7). This payback period is without considering labor savings and potential increased revenue because of improved flavor.

Table 7: Annual savings and payback period of method of the invention

Capital cost to client	Annual costs of traditional method	Annual costs of method of invention	Annual Savings	Payback period
\$17,000.00	\$7,040.12	\$3,155.97	\$3,884.15	4.38

Additionally, it can be speculated that the method of the invention will save brewers an average of 6 hours of carbonation time per batch, assuming each batch traditionally takes 8 hours to carbonate. Annually, the method of the invention has the potential to save 2700 hours in labor. Each hour of labor is estimated at \$15, and thus the method of the invention can save \$40,500 annually. Based on this, the total benefit of the invention is \$44,384.15. The payback period for the client to make back their initial capital investment is 0.38 years

Table 8: Annual savings and payback period of the method of the invention considering labor savings

Capital cost to client	Annual costs of traditional method	Annual costs of method of invention	Annual savings	Additional labor savings	Total economic benefit	Payback period (years)
\$17,000.00	\$7,040.12	\$3,155.97	\$3,884.15	\$40,500	\$44,384.15	0.38

If it is shown that the flavor and quality of the beer produced by the method of the invention are notably different than the traditional carbonation method, it can be projected that additional revenue from the sale of higher quality beer will further increase the economic benefit. If the client desires a payback period of 18 months and doesn't account for labor savings, then the additional economic benefit beyond CO₂ and electricity savings needs to be \$7450. If 450 batches are produced a year, then each batch will need to cost \$16.56 more to recover this cost. This means that each six-pack only needs to cost \$0.0075 more for the client to have a payback period of 18 months. If the higher quality beer is sold for \$1.00 more than the typical six-pack price, around \$9.50, then the potential for additional revenue is \$2404.44 per batch, and \$920,000 annually for a simple payback period of 0.018 years.

Recommendations for Future Flavor Testing of Beer

As was initially planned in this work, it is recommended that flavor testing and analysis in quality differences between the two methods of carbonation be conducted. For this testing, a recommended method of testing was developed as part of this work so that any notable flavor or quality differences between the beer produced by each method can be determined. To conduct this research, three styles of beer from Core Brewing Company in Bentonville, Arkansas will be analyzed: an American red ale, a hefeweizen, and an India Pale Ale. The selected beers are Core Brewing Company's Razorback Red, Heisenberg, and Ouachita IPA. These three different beer types may respond to flavor stripping from bubbling differently and may have different resulting effects from the different carbonation treatments. A summary of each beer type and its properties can be found in Table 9.

Table 9: Summary of Characteristics of Selected Beer Types from Core Brewing Company (Core Brewing Company, 2018)

Beer Type	Name	ABV	Hops	Descriptors
American Red Ale	Razorback Red	5.2%	Crystal	Sweet base malt, rye, chocolate
Hefeweizen	Heisenberg	5.5%	Crystal	Banana and vanilla aromatics, spicy and fruity taste
India Pale Ale	Ouachita IPA	6.8%	Columbus, Centennial, Cascade, Rahr, Simcoe	Clean finish, strong pine aroma

Each beer type is currently in commercial production and will be produced as normal with a 40-barrel batch. Prior to the carbonation step, the batch will be split in half with one 20-barrel half carbonated with the traditional bubble method and one half using the method of the invention. Each of these batches will be carbonated using a procedure resulting in the same amount of carbonation time. Carbonation will occur in two twenty-barrel brite tanks to the same final carbonation level indicated by the Gehaltemeter (Haffmans, 2015). Each type of beer will be canned using the same method, and a random sub-sample of at least 240 ounces (20-12 oz cans) from each carbonation method will be selected for a total of 1440 ounces (120 cans) (480 oz-40 cans of ale, 480 oz-40 cans of hefeweizen, 480 oz-40 cans of IPA). The beer will be transported and stored under refrigeration at 2 °C until testing occurs.

A triangle test will be conducted by untrained sensory panelists at the Food Science Department, University of Arkansas, Fayetteville, AR. A total of seventy panelists will participate in the triangle test. This number of judges was determined based on Figure 9, with 90% power, alpha at 0.05, and delta at 1.5 standard deviations. Based on these parameters, a minimum of 66 judges is required. For a margin of safety, 70 panelists will participate in the testing (4 judges above the minimum requirement).

δ	2-AFC	Duo-trio	3-AFC	Triangle
80% power				
0.50	78	3092	64	2742
0.75	35	652	27	576
1.00	20	225	15	197
1.25	13	102	9	88
1.50	9	55	6	47
1.75	7	34	5	28
2.00	6	23	3	19
90% power				
0.50	108	4283	89	3810
0.75	48	902	39	802
1.00	27	310	21	276
1.25	18	141	13	124
1.50	12	76	9	66
1.75	9	46	6	40
2.00	7	31	5	26

Abstracted from Ennis (1993)

Figure 9: Number of judges required for different levels of power and sensory difference for paired comparison (2-AFC), duo-trio, 3-AFC, and triangle tests with $\alpha = 0.05$ (Lawless and Heymann, 2010)

The panelists will be instructed to palate cleanse with water before the test. The triangle test is “forced-choice,” meaning the panelists must select a sample and cannot respond “no difference.” Alpha risk and beta risk will be set at 0.05. From the panelists’ responses, it will be determined if a perceptible difference between the samples exists. Statistical analysis will be conducted using chi-square test to determine if a statistically significant difference exists between the two treatments. Flavor descriptors will also be collected from the trained panel and compared between treatments.

Conclusion

An analysis of the difference between the traditional carbonation method and the method of the invention has indicated that the economic and time savings of the invention are significant. The invention does not waste any CO₂ and is able to carbonate the same volume of beer for less

money and time. It is recommended that flavor and quality evaluations are conducted in the near future, so that it can be determined if there are any significant differences between beer carbonated by the traditional method and beer carbonated by the method of the invention.

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